Near-Axial Interference Effects for Long-Range Sound Transmissions through Ocean Internal Waves

Natalie S. Grigorieva
Department of Applied Mathematics and Mathematical Modeling
St. Petersburg State Marine Technical University
3, Lotsmanskaya str., 190008, St. Petersburg, Russia
phone: (+7)-812-784-0688 fax: (+7)-812-784-0688 email: nsgrig@natalie.spb.su

James Mercer, Jeffrey Simmen, Michael Wolfson
Applied Physics Laboratory, University of Washington
1013 NE 40th Street, Seattle, Washington 98105-6698
phone: (206) 543-1361 fax: (206) 543-6785 email: mercer@apl.washington.edu

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LONG-TERM GOALS

The long-term goal of this effort is to provide an improved way of interpreting the experimentally observed time-of-arrival patterns in long-range, low-frequency propagation in the deep ocean.

OBJECTIVES

In many long-range propagation studies the source and receiver are placed close to the depth of the waveguide (SOFAR) axis to minimize the interaction of the acoustic field with the ocean's surface and bottom. The most pronounced characteristics of the time-of-arrival patterns for these experiments are early geometric-like arrivals followed by a crescendo of energy that propagates along the axis. In Fig.1 adapted from one published in Ref. (1) these characteristics are clearly shown for a time-of-arrival pattern measured during the Acoustic Engineering Test (AET) of the Acoustic Thermometry of Ocean Climate (ATOC) project conducted in the eastern North Pacific Ocean.

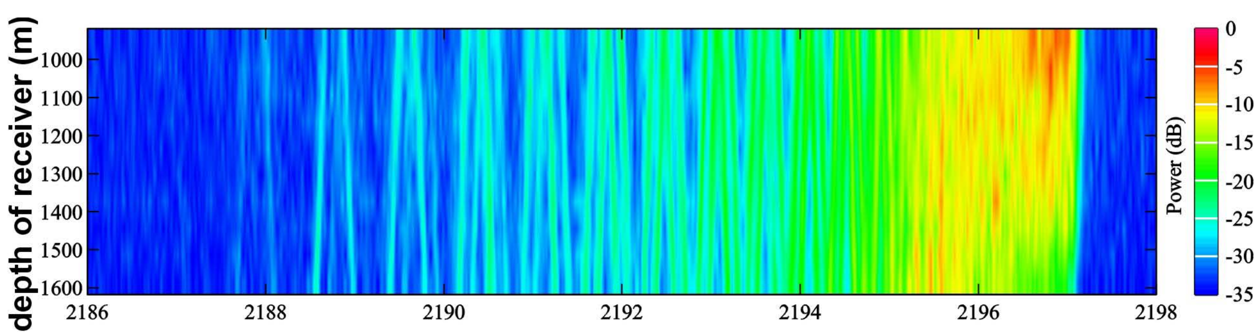

Figure 1. The time-of-arrival pattern measured during the AET experiment

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14. ABSTRACT
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15. SUBJECT TERMS

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While the eikonal equation can be solved for the ray paths and travel times can be calculated by integrating the index of refraction along the ray paths, it is impossible to use geometrical acoustics to describe the propagation of energy along the waveguide axis because of the presence of caustics with caustic cusps located repeatedly along the axis. Figure 2 illustrates this pattern of caustics. It is a ray tracing for a source on the axis (and for relatively short ranges). In neighborhoods of cusped caustics a very complicated interference pattern is observed. The neighborhoods of interference grow with range and at long ranges they overlap.

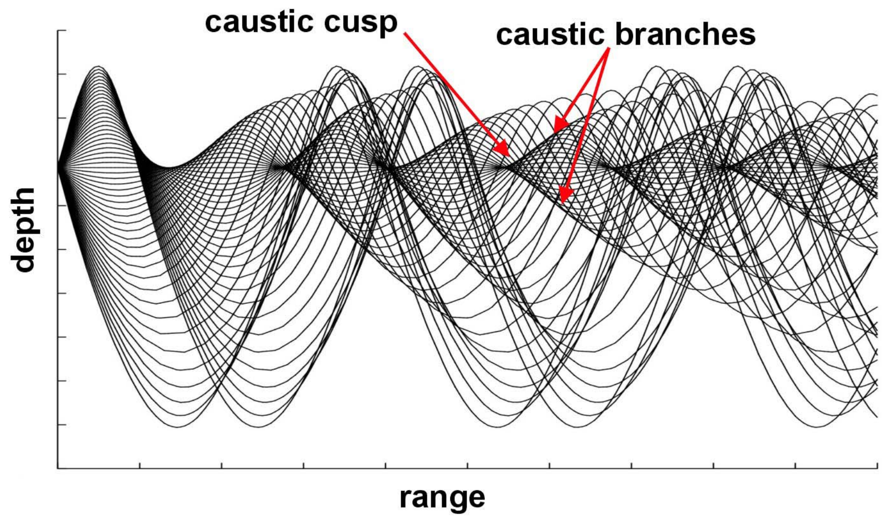

Figure 2. Ray tracing for a source on the axis of a waveguide

The overall goal of the research is to provide a better understanding of the interference effects that are present for sound propagation in a ducted waveguide when the source and receiver are located near or on the axis of the duct. The primary application of this work will be the improved interpretation of time-of-arrival patterns observed in long-range acoustic propagation experiments in the ocean.

APPROACH

It is well known that in the neighborhood of a simple caustic the acoustic field is described by the Airy function. To describe the acoustic field in the neighborhood of a cusp of a caustic it is necessary to use the Pearcey integral. The longitudinal and transverse sizes of the neighborhood of a cusp of a caustic, where the geometrical acoustics formulas are not applicable, increase with range. As a result, at a certain propagation range the neighborhoods of adjacent cusps overlap. In this case the acoustic field cannot be described by the Pearcey integral and the more complicated interference structure appears. For a very idealized model of a symmetric waveguide, Buldyrev in Ref. (2) showed that the interference of the wave fields that correspond to near-axial rays, and is associated with the cusped caustics, leads to formation of a coherent structure that propagates along the waveguide axis like a wave. This structure was called “the axial wave”.

Buldyrev’s work on the axial wave was done before the long-range experiments took place and with the purpose of obtaining a global description of propagation in the presence of cusped caustics. The project entitled “Investigation of Near-Axial Interference Effects in Long-Range Acoustic Propagation in the Ocean" (Award Number: N00011402M0233; Principal Investigator – N. Grigorieva) was devoted to application of the method proposed by Buldyrev to ocean models typical for long-range propagation experiments. Within the scope of this project and during the first 6 months of work on the present project (FY06) the following results were obtained.

The two-dimentional reference point source problem with the parabolic index of refraction squared was studied in detail in Refs. (3) and (4). The integral representation of the exact solution was transformed in such a way to extract ray summands corresponding to rays radiated from the source at angles less than a certain angle, the axial wave, and a term corresponding to the sum of all the rays having launch angles greater than the indicated angle. The obtained results were discussed at the 143rd ASA Meeting in Pittsburg; see Refs. (5) and (6).

For an arbitrary range-independent deep-water waveguide the formula for the axial wave can be obtained as well by transforming the integral representation of the exact solution of the point source problem. But this method is not applicable to the range-dependent medium. That is why it was important to propose another method for obtaining the integral representation of the axial wave admitting the generalization to the range-dependent medium and giving the same result as the transformation of the exact solution. Taking into account the formula for the axial wave in the case of the two-dimensional reference point source problem, it was natural to assume that for an arbitrary deep-water waveguide in a two-dimensional range-independent ocean the axial wave will have the similar integral representation and try to find its integrand in the form of a product of the weight function and asymptotic expansions of solutions to the Helmholtz equation that are concentrated near the sound-channel axis. These solutions have the form of the exponentials multiplied by the parabolic cylinder functions whose arguments are sections of series in –1/2 powers of a cyclic frequency. For an arbitrary range-independent deep-water waveguide the required solutions to the Helmholtz equation were derived in Ref. (7). Using them, the integral representation of the axial wave for an arbitrary waveguide in a two-dimensional range-independent meduim was obtained in Refs. (8) and (9). Numerical computations were carried out for the canonical sound-speed profile. The source frequency was taken equal to 75 Hz, and the propagation range was 3000 km.

The integral representaion of the axial wave obtained in Refs. (8) and (9) was generalized to a three-dimensional range-independent medium in Ref. (10). Through numerical simulations, the dependencies of the axial wave on range, sound-speed profile properties, and geometry of the experiment were studied for two sound-speed profiles: the average profile from the AET experiment and the Munk canonical profile.

The integral representation of the axial wave in the time domain for a range-independent ocean was obtained in Refs. (11) and (12). Numerical computations were done for the Munk canonical sound-speed profile. A signal with the center frequency of 75 Hz and 30-Hz bandwidth was used for modeling. The propagation range was 3250 km. Numerical simulations for the average profile from the AET experiment were included in Ref. (13).

As it was noted above, the main advantage of the proposed method for obtaining the integral representation of the axial wave in a range-independent medium, see Refs. (8) and (9), is that all the steps of this method admit generalization to a range-dependent ocean. It means that to derive the integral representation of the axial wave in a range-dependent ocean it was necessary to start with obtaining the solutions to the Helmholtz equation that are concentrated near the sound-channel axis and have the form described above; see Ref. (14). As opposed to the adiabatic approximation of low-order modes that depend only on medium properties along a vertical line parallel to the Z-axis, the newly obtained solutions to the Helmholtz equation provided in Ref. (14) accumulate the information about medium properties near the range-variable sound-channel axis along the whole propagation range.

In Refs. (15) and (16) the integral representation of the axial wave in a range-dependent ocean was derived in the form of a linear superposition of the solutions to the Helmholtz equation concentrated near the axis of a deep-water waveguide. The weight function was selected in such a way that the localization principle holds. In the limiting case of a range-independent ocean, this principle allows one to use the integral representation of the axial wave obtained in Refs. (9) and (10). Numerical simulations in Refs. (15) and (16) were carried out for a deterministic model of a range-dependent ocean, where the horizontal inhomogeneity results from the change in geographic location. The model is based on the information about sound-speed profiles as a function of range between the source and receiving array derived from the WOA'94 climatology for November along the path of the AET experiment , see Fig. 5 of Ref. (1).

The effect of a local deterministic inhomogeneity on the axial wave was studied in Ref. (17). The perturbation is induced by a cold mesoscale eddy embedded in a sound channel with the sound-speed profile typical for the AET experiment. The frequency of the source was taken equal to 75 Hz. It was shown that after passing over the mesoscale eddy its effect on the diffractive component of the acostic field as a function of range or depth remains substantial even at a distance equal to 2000 km from the eddy.

WORK COMPLETED

In FY07 the main goal of the research was to find out if it is possible or not to detect the axial wave in the Long-Range Ocean Acoustic Propagation Experiment (LOAPEX) conducted in the North Pacific Ocean in September-October 2004. To answer on this question we used the conductivity, temperature, and depth data measured at seven different ranges from the vertical line array (VLA): at the stations T3200, T2300, T1600, T1000, T500, T250, and T50. At 0-range (at the VLA) the same sound-speed data were used as present at 50 km from the VLA. To simulate the axial wave in a range-dependent ocean, the smooth two-dimensional sound-speed field was obtained and the sound-channel axis was calculated as well as the sound-speed at the axis. The depth of the sound-channel axis increases as one proceeds to the array from 862.535 m at 3200 km from the VLA up to 635.678 m.

To evaluate the maximal possible interference effect near the sound-channel axis, the transmission loss of the axial wave in the range interval 3150 – 3200 km was simulated at the frequency of 68.2 Hz with the source and receiver placed on the sound-channel axis. It was shown that the transmission loss changes in the interval (-120 dB, -117 dB). The axial wave falls off with distance as the range to –3/4 power. The transmission loss as a function of depth of the source placed at 3200 km from the VLA monotonically decreases as the distance between the source and the sound-channel axis increases. At the frequency of 68.2 Hz when the depth of the source is 500 m, the transmission loss is –192.683 dB. In the experiment the source level was about 194 dB. Thus, the axial wave is not detectable in the case when the propagation range is 3200 km and the depth of the source is 500 m.

At the next two stations T2300 and T1600 the distance between the source and the sound-channel axis, H, is too large as well. If the propagation range is equal to 2300 km, we get H = 328.1 m and at 1600 km this distance is 421.4 m (for the source deployed to 500 m and 350 m respectively). The axial wave is not detectable as well. The source deployed to 800 m depth at the stations T1000, T500, T250, and T50 generated axial waves that can be detected.

The characteristic property of the axial wave that could be used to detect this wave is its arrival time. For the station T1000 at the frequency of 75 Hz the axial wave arrives at the receiver 36.8 ms later than the lowest mode in the adiabatic approximation. The difference is equal to 37.7 ms and 21.9 ms at the frequency of 56.25 Hz and 93.75 Hz respectively. The delay of the axial wave decreases as the propagation range decreases. That is why all the following simulations were carried out for the station T1000, where the difference in the arrival time between the axial wave and the lowest mode is the largest.

In the frequency domain one transmitted m-sequence in the LOAPEX is well approximated by a signal with the central frequency of 75 Hz and 37.5-Hz bandwidth. Numerical simulations showed that the peak of intensity of the axial wave arrives later than the peak of intensity of the lowest mode in the adiabatic approximation by about 27 ms. In comparison with the wave traveling directly along the sound-channel axis (had it existed), the resolution width of the pulse corresponding to the axial wave and its rms signal duration increase by approximately 50%.

The time interval equal to 27 ms is detectable in the experiment. If in the ocean perturbed by internal waves the delay of the axial wave relative to the arrival time of the lowest mode would keep or increase its value and the maximal value of the pulse corresponding to the axial wave would be high enough in comparison with the noise level, this would mean that for the source deployed to 800-m depth at the station T1000 the axial wave is detectable. As a result, we would get the new important information about medium properties.

To study the effect of the environmental variability on the axial wave we used a quite simple (but realistic) model for acoustic fluctuations due to internal waves. Simulations were based on the buoyancy frequency profile from the LOAPEX CTD station T50. Using measured data, their smooth approximation was obtained. To simplify the description of the sound-speed fluctuations, we chose a single wave frequency corresponding to semi-diurnal tide and considered the sound-speed fluctuations induced by the first 10 modes of the internal wave field. Modes 1-10 introduce the ocean structure with horizontal wavelengths ranging from 150 km down to 15 km.

In the ocean perturbed by the internal wave field simulations of signal propagation for a part of the acoustic field corresponding to the axial wave were faced with essential problems. To understand the nature of these problems, we made calculations for a set of medium models, where the sound-speed perturbations due to internal waves were added to the unperturbed range-dependent sound-speed profile being multiplied by the coefficient K. This coefficient was taken equal to 0.075, 0.09, and 0.15. It was shown that when the coefficient K increases, the maximum value of the intensity decreases dramatically. For the coefficient K equal to 0.15 the maximum value of the intensity decreases by 23 dB if to compare with the intensity of the axial wave in the ocean without internal wave field. This behavior of the axial wave is the result of the effect of the internal wave field on coefficients in the integral representation of the axial wave. In the unperturbed ocean these coefficients are slightly oscillating, but even at K equal to 0.075 they become strongly oscillating. So, taking into account the environmental variability induced by ocean internal waves, we get too low received intensity of the axial wave to be detected at the VLA.

The results for simulation of the axial wave for the LOAPEX CTD data formulated above were reported at the 4th Joint Meeting of the Acoustical Society of America and the Acoustical Society of Japan in Honolulu, Hawaii, 28 November – 2 December, 2006; they were included in the talk "Effect of ocean internal waves on late arrivals for the LOAPEX CTD data" by N. Grigorieva and G. Fridman given at the Tenth North Pacific Acoustic Laboratory (NPAL) Workshop, Sleeping Lady, Washington, 14 – 17 May, 2007 and discussed at the Applied Physics Laboratory, University of Washington, Seattle in December 2006 and in May 2007. The last obtained results will be reported at the 154th Meeting of the Acoustical Society of America, which will be held 27 November – 1 December 2007 in New Orleans, Louisiana.

RESULTS

Considering the range-dependent ocean model based on the LOAPEX CTD data measured at 7 different ranges from the VLA, we concluded that for the stations T3200, T2300, and T1600 the received intensity of the axial wave was too low to be detected at the VLA because of the large distance between the sound source and the waveguide axis. The source deployed to 800 m depth at the stations T1000, T500, T250, and T50 generated axial waves that can be detected.

It was learned that the characteristic property of the axial wave that could be used to detect this wave is its arrival time. For the station T1000 at the frequency of 75 Hz the axial wave arrives at the receiver 36.8 ms later than the lowest mode in the adiabatic approximation. The difference in the arrival times is equal to 37.7 ms and 21.9 ms at the frequency of 56.25 Hz and 93.75 Hz respectively.

It was concluded that in the frequency domain one transmitted m-sequence in the LOAPEX is well approximated by a signal with the center frequency of 75 Hz and 37.5-Hz bandwidth. For the station T1000 the peak of intensity of the axial wave arrives later than the peak of intensity of the lowest mode in the adiabatic approximation by about 27 ms. In comparison with the wave traveling directly along the waveguide axis (had it existed), the resolution width of the pulse corresponding to the axial wave and its rms signal duration increase by approximately 50%.

The time interval equal to 27 ms is detectable in the experiment. Thus, if in the ocean perturbed by internal waves the delay of the axial wave relative to the arrival time of the lowest mode would keep or increase its value and the maximal value of the pulse corresponding to the axial wave would be high enough in comparison with the noise level, this would mean that for the source deployed to 800-m depth at the station T1000 the axial wave is detectable. As a result, we would get the new important information about medium properties.

It was learned that even for the simplest model of acoustic fluctuations induced by the first 10 modes of the internal wave field with a single wave frequency corresponding to semi-diurnal tide the received intensity of the axial wave becomes too low to be detected at the VLA. This conclusion complies with the results of the LOAPEX experiment.

IMPACT/APPLICATIONS

The primary application of this work is the interpretation of time-of-arrival patterns observed in long-range ocean acoustic propagation experiment. In the frequency domain one transmitted m-sequence in the LOAPEX is well approximated by a signal with the center frequency of 75 Hz and 37.5-Hz bandwidth. The computations show that for the station T1000 the peak of intensity of the axial wave arrives later than the peak of intensity of the lowest mode in the adiabatic approximation by about 27 ms. But taking into account the effect of the environmental variability caused by internal waves we get too low received intensity of the axial wave to be detected at the VLA.

RELATED PROJECTS

This work falls within the context of the ONR Ocean Acoustic Program (Code 321OA) S&T Thrust, Long-Range Propagation and complements other Code 321OA theoretical works.

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